Project Title: Identification and Prioritization of Karst Groundwater Basins in Kentucky for Targeting Resources for Nonpoint Source Pollution Prevention and Abatement

Joseph A. Ray, Phillip W. O'dell, and Jack R. Moody
Technical Services Section

Jolene M. Blanset and Robert J. Blair
Data Management and Support

Groundwater Branch
Kentucky Division of Water
14 Reilly Road
Frankfort, Kentucky 40601

Grant Number: C9994861-97
Workplan Number: 97-17
Report Period: 1997-2004

FINAL
January 14, 2005

The Environmental and Public Protection Cabinet (EPPC) and Kentucky Division of Water, Groundwater Branch do not discriminate on the basis of race, color, national origin, sex, age, religion, or disability. The EPPC and Kentucky Division of Water, Groundwater Branch will provide, on request, reasonable accommodations including auxiliary aids and services necessary to afford an individual with a disability an equal opportunity to participate in all services, programs and activities. To request materials in an alternative format, contact the Kentucky Division of Water, 14 Reilly Road, Frankfort, KY, 40601 or call (502) 564-3410, or contact Kentucky Division of Water, Groundwater Branch. Hearing and speech-impaired persons can use the Kentucky Relay Service, a toll-free telecommunications device for the deaf (TDD). For voice to TDD, call 800-648-6057. For TDD to voice, call 800-648-6056.

Funding for this project was provided in part by a grant from the U.S. Environmental Protection Agency (USEPA) through the Kentucky Division of Water, Nonpoint Source Section, to Kentucky Division of Water, Groundwater Branch as authorized by the Clean Water Act Amendments of 1987, §319(h) Nonpoint Source Implementation Grant #C9994861-97. Mention of trade names or commercial products, if any does not constitute endorsement.

ACKNOWLEDGEMENTS

The authors wish to thank Peter Goodmann and David Leo of the Groundwater Branch for conceiving the scope of this project, developing the work plan, and providing valuable guidance. We thank Corrine Wells, Joseph Ferguson, and other members of the Nonpoint Source Section of the Water Quality Branch for helpful advice, and for providing a conference forum for presenting interim reports and maps. Jolene Blanset constructed boxplot illustrations, performed statistical analyses, and devised the methodology for prioritizing karst basins. Robert Blair digitized and calculated geographic data, illustrated dye-trace data, and constructed land cover maps. Pat Keefe, Tracy Burgess III, Bruce McKinney, and Beverly Oliver of the Groundwater Branch, and Tom Nicotera of the Bowling Green Regional Office of the Division of Water provided assistance with dye-tracing activities and water sampling. James Webb and Peter Goodman reviewed drafts of the final report and made numerous suggestions and improvements.

Loren Boggs of Hopkinsville, Donnie Owens, of Elkton, and Lonnie Stewart, of Cadiz were helpful at regional Natural Resource Conservation Service (NRCS) offices. The following personnel of the Kentucky Cooperative Extension Service provided assistance: Curt Judy of Todd County, Jason P'Pool of Trigg County, and J. Stone of Christian County. Ernest Collins, David Stipes, Curtis Kirk, and J.D. Green provided assistance with compiling agricultural best management practices.

Caving organizations are commonly called Grottos and are often useful sources of cave and spring data. Angelo George of the Louisville Grotto assisted with vital karst data for the Northeast study area and Jim Greer provided dye-trace and discharge data for the Boiling Springs basin. Russell Kyler of the Golden Pond Grotto and Preston Forsythe of the Western Kentucky Speleological Survey provided karst data and background information for the Southwest study area.

Ralph Ewers and Pete Idstein of Ewers Water Consultants assisted with coordination of simultaneous field studies in the Southwest study area, north of Fort Campbell Military Reservation, and provided valuable help with tracer-dye analysis. Charles Taylor of the Kentucky District of the US Geological Survey (USGS), helped coordinate simultaneous field studies in the Northeast study area. Jim Currens and Randy Paylor of the Kentucky Geological Survey (KGS) provided field assistance with tracer injections in the Northeast study area. Sergeant Bob Marango, of the US Department of Fish and Wildlife Resources, provided a boat trip along the banks of the Ohio River in order to complete a spring survey in the Northeast study area.

We thank Maleva Chamberlain, Pat Risk, and Tina Satterly of the Division of Water for assistance with scanning of illustrations, and Henry Francis and Karen Cisler of the KGS for help with processing many water-samples and documentation of the results. Finally, without the numerous landowners and farmers who graciously granted access to their property for fieldwork, this extensive study could not have been possible.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLES

CONVERSION FACTORS

Multiply	by	To obtain
acre	43559.66	ft^2
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
gallon (gal)	3.785	liter (L)
gallon per minute (gpm)	0.06308	liter per second (L/s)
cubic feet per second (ft^3/s)	0.02832	cubic m per second (m^3/s)
$ft^3/s/mi^2$ (cfsm)	10.931	$L/s/km^2$ (lsk)
foot per mile (ft/mi)	0.1894	meter per km (m/km)
square mile (mi^2)	640.0	acres
mi^2	2.590	km^2
acre (ac)	0.4047	hectare (ha)
ounce (oz)	28.35	gram (g)
pound (lb)	0.454	kilogram (kg)
km	0.621	mi
$L/s/km^2$	0.0915	$ft^3/s/mi^2$
km^2	0.386	mi^2
meter	3.28	feet
m^3/s	35.31	ft^3/s
m/km	5.28	ft/mi
kg	2.20	lb
hectare	2.471	acre

Miscellaneous abbreviations:

BMP - Best Management Practice
DOW - Division of Water
EPA – U. S. Environmental Protection Agency
ft^3/s - Cubic Feet per Second
GQ - Geological Quadrangle
GIS - Geographic Information System
HA - Hydrologic Investigation Atlas
HAL - Health Advisory Level
KGS - Kentucky Geological Survey
L/s - Liters per Second
MCL - Maximum Contaminant Level
MDL - Minimum Detection Level
mg/L - milligrams per liter (parts per million)
NE - Northeast Study Area
NPS - Nonpoint Source
ppm - parts per million
QA/QC - quality assurance/quality control
SMCL - Secondary Maximum Contaminant Level
SW - Southwest Study Area
TMDL - Total Mean Daily Loading
UBF - Unit Base Flow (base flow per unit area)
USGS - United States Geological Survey

EXECUTIVE SUMMARY

This project investigated the water quality of 12 large karst springs, their drainage basins, and several neighboring basins in the Pennyroyal Plateau over a four-year period. The purpose was to identify and evaluate impacts from nonpoint source (NPS) pollution in sensitive karst watersheds of north-central and western Kentucky. Ninety-six quarterly water-quality samples were collected at these large springs from January 1999 through May 2001. Key parameters that reflect NPS pollution include nutrients and herbicides, applied mainly to row crops. Nitrate-N and atrazine were of special concern because of moderate to elevated levels measured in the spring waters. Nitrate-N levels fluctuated somewhat throughout the study period with medians ranging from about 1-6 mg/L (compared to the Maximum Contaminant Level [MCL] allowed in public drinking water of 10 mg/L). Atrazine detections peaked in the spring application season, sometimes well above the MCL of 0.003 mg/L.

Karst terrane is well known for complex groundwater drainage systems, which are sensitive to pollution. In order to correctly attribute NPS impacts observed at springs to the appropriate watersheds, groundwater-tracing studies were conducted from 1997-2000 to more accurately identify basin boundaries. Two major areas were investigated in this project: the northeastern (NE) portion of the Pennyroyal Plateau, primarily in Meade and Breckinridge counties, and the southwestern (SW) portion of the Pennyroyal Plateau, largely in Christian and Trigg counties.

Forty-two groundwater tracer tests were completed and 261 km (162 mi) of subsurface flow routes within 19 groundwater basins were mapped for the first time or replicated. These basins represent total land areas of 670 km^2 (258 mi^2) and base-flow water supply of 850 L/s (30 ft^3/s). This improved mapping of complex karst watersheds can be used to more accurately develop Total Mean Daily Loading (TMDL) assessments of regional streams. The Kentucky Geological Survey in cooperation with the Kentucky Division of Water will also publish subterranean flow-route and groundwater basin-boundary data in the karst-atlas mapping project. The study areas are located on the Tell City (NE) and Hopkinsville (SW), 1:100,000 quadrangles.

An additional assessment of watershed area and aquifer yield (base flow per unit area or UBF) was achieved by measuring spring discharges during dry-season base-flow conditions. Thirty-two springs were gaged in combined study areas, from 1997-2001, resulting in the following conclusions:

(a) A direct relationship exists between base-flow discharge and basin area, within uniform hydrogeologic setting. However, UBF in the SW study area is 25%-30% greater than in comparable areas of the NE. This is likely due to slightly higher rainfall and increased groundwater storage within thicker soils of the SW study area.

(b) Within the NE study area, basins typified by sinkhole-plain topography yielded twice the UBF as did basins draining dissected sandstone caprock. This is a consequence of greater sustained groundwater storage in soil-mantled limestone than in sandstone-capped plateaus.

After spring-basin boundaries were delineated, digital land-cover data were evaluated to quantify the variety and concentration of agricultural activities. Based on average percentage of row

crops and pasture and hay, the SW study area, which is more level and arable, contains about twice the number of acres in agriculture versus the NE study area. Conversely, the more rugged NE study area is covered by four times more deciduous forest than in the SW. These fundamental differences result in better overall water quality in the NE than in the SW.

Based on water quality and land use, the impacts of NPS pollution of these karst springs and basins were ranked and prioritized. As expected, the more intensive agricultural basins of the SW generally ranked higher on this priority list than those in the NE. This priority ranking can be used to more appropriately focus resources to address NPS pollution, such as education and training, technical and financial assistance, and best management practice (BMP) implementation and modification.

Education outreach has been accomplished by participation in agriculture field meetings, karst field trips and regional watershed meetings. Groundwater maps and data have been and will be distributed to landowners and stakeholders. A poster summarizing the final report will be presented at conferences and distributed to government agencies and the public. The completed report will also be available at the Kentucky Division of Water website. Additionally, the karst-basin delineation and the priority ranking methods can be used as technical guidance for evaluating NPS pollution within similar complex karst groundwater basins.

Rank	***Spring***		***Weighted Value***
	Southwest	***Northeast***	
1	River Bend		9.15
2	Wright		8.83
3	Mill Stream		7.83
4	King		7.53
5	Cooks		7.10
6	Barkers Mill		6.88
7		French Creek	6.88
8	Walton		6.53
9		Boiling	5.68
10		Buttermilk Falls	4.05
11		Head of Wolf	4.00
12	Brelsford		3.58

Nonpoint-Source Pollution Priority Ranking of Twelve Sampled Karst Springs

ID #	Spring	Discharge L/s*	Basin Area km^2	% Agri.	% Forest	Maximum Nitrate-N mg/L	Maximum Atrazine mg/L[B]	Weighted Score	Priority Rank
0860	River Bend	158.6	69.9[m]	87.7	8.7	6.19	**0.00315**	9.15	**1**
1475	Wright	25.5	14.2	89.7	6.2	7.05	0.00115	8.83	**2**
0203	Mill Stream	82.1	182.1[m]	73.8	21.9	6.73	0.00299	7.83	**3**
1489	King	59.5	28.2	85.2	11.5	4.81	**0.00993**	7.53	**4**
1141	Cook	93.4	41.7[m]	75.3	17.1	5.49	**0.00615**	7.10	**5**
0859	Barkers Mill	169.9	69.2[m]	93.0	3.0	6.19	0.00074	6.88	**6**
1838	French Creek	45.3	54.4	67.9	27.2	3.59	**0.00675**	6.88	**7**
1457	Walton	48.1	25.1	77.4	19.0	6.24	**0.0119**	6.53	**8**
0855	Boiling	277.5	327.6	52.7	45.6	3.03	0.00067	5.68	**9**
1824	Buttermilk Falls	22.7	12.7*est*	26.8	65.1	2.21	**0.00393**	4.05	**10**
1063	Head of Wolf Cr.	14 *est*	42.5	27.9	70.1	1.04	0.00294	4.00	**11**
1448	Brelsford	85 *est*	32.9	65.4	31.1	2.64	0.00145	3.58	**12**

Summary of Numerical Data Derived by this Investigation
(*Discharge during dry-season base-flow conditions; [m] Basin areas have been modified by subsequent research; **[B]** Bold font indicates atrazine concentration above MCL)

INTRODUCTION

More than a decade ago, the US Environmental Protection Agency (EPA) began to recognize that nonpoint source pollutants from groundwater discharge were a significant source of contaminant loading in many surface waters throughout the US (Hoffer, 1991). More recently, the USGS showed that the lower Ohio River basin, draining a considerable amount of karst terrane within the Cumberland River and Green River watersheds in Kentucky, has some of the highest yields of pesticide runoff in the US (Crain, 2002). Although pesticide runoff from non-karst farmlands has been shown by the Division of Water to be a serious and increasing pollution problem in the lower Green River basin (Schaffer and Miller, 2002), the sensitive groundwater drainage of extensive karst terranes in the region is also a major contributor.

Soluble rocks, such as limestone, on which karst landscapes form, underlie more than 50% of Kentucky. This terrane is considered to be karst because of the development of turbulent groundwater circulation through underground channels or conduits. Well-developed karst may contain naturally occurring closed topographic depressions or sinkholes with internal drainage, losing or sinking streams, caves and large springs. Because of these features, most of the groundwater in Kentucky's karst drainage basins is under the direct influence of the surface by rapid infiltration of precipitation and surface-runoff water. Consequently, karst groundwater is widely recognized as highly sensitive to point- and nonpoint-source pollution from surface activities such as agriculture, transportation and urban development. Although several aquifer studies have been undertaken within Kentucky's Mississippian Plateau, few broad-scale investigations of karst groundwater have been conducted in the most intensive agricultural areas.

The Technical Services Section of the Kentucky Division of Water's Groundwater Branch conducted a groundwater investigation in which the primary goal was to produce a priority ranking of karst groundwater basins in areas of intensive agricultural land use in the Mississippian Plateau physiographic province of Kentucky. This ranking of karst groundwater basins will provide a framework to appropriately focus future nonpoint-source resources, such as BMP implementation and modification, public education and technical and financial assistance in areas that have been established to have the most critical need.

PURPOSE AND SCOPE

This project studied 12 karst springs and several neighboring basins during two years for the purpose of identifying impacts from NPS pollution. Most karst drainage basins assessed by the study were previously unknown or known by limited data. Methods such as hydrogeologic inventory, tracer testing and unit base-flow measurements were employed in order to identify the basin drainage areas so that key water quality parameters can be attributed to appropriate karst watersheds. The primary objective of this project is a priority ranking of the 12 karst basins, as assessed by eight quarters of water quality analyses of the main springs and land use within their basins.

LOCATION AND EXTENT OF STUDY AREAS

Two primary study areas encompassing Mississippian-aged rocks of the Pennyroyal Plateau physiographic region were assessed during this investigation. Northeastern and southwestern sub-regions were evaluated and are shown in Figure 1.

The NE study area is located in Meade, Breckinridge and Hardin counties, where four springs were sampled and 24 groundwater tracer tests were conducted in 10 karst drainage basins. This study area covers about 775 km^2 (300 mi^2 or 192,000 acres) and includes all or part of the New Amsterdam, Mauckport, Lodiburg, Irvington, Guston, Rock Haven, Hardinsburg, Garfield, Big Spring, Kingswood, Custer and Constantine 7.5 minute topographic quadrangles.

The SW study area is located in Trigg, Christian and Todd counties, where eight springs were sampled and 18 tracer tests were conducted in nine karst drainage basins. The study area covers about 390 km^2 (150 mi^2 or 96,000 acres) and includes all or part of the Cobb, Gracey, Cadiz, Caledonia, Church Hill, Johnson Hollow, Roaring Spring, Herndon, Oak Grove, Trenton, Guthrie, and Allensville 7.5 topographic quadrangles.

HYDROGEOLOGIC SETTING

Within the two regional study areas, the principal aquifer occurs in Mississippian-aged limestones of the Pennyroyal or Mississippian Plateau. In a broader context, this cavernous limestone region coincides with most of the Highland Rim Section of the Interior Low Plateaus region of central and western Kentucky. In some locations, especially the northeastern study area, karst drainage extends beneath the dissected uplands developed in Chester-age sandstones and limestones.

STRATIGRAPHY

Rocks within the study areas consist mainly of thick units of Ste. Genevieve and St. Louis limestones of the Meramecian Series of the Mississippian System (Figure 2). These limestones were deposited mainly in shallow seas. The purity and high solubility of the limestones make the terrane highly susceptible to karst development. Long-term bedrock dissolution of these limestones has strongly influenced the Pennyroyal’s characteristic flat-lying to undulating topography, which contains numerous shallow sinkholes and caves, losing and sinking streams, stream-less valleys, intermittent lakes and large springs.

The relative stratigraphic position of springs discharging from the Ste. Genevieve and St. Louis limestones are shown in Figure 2 with a spring symbol and are labeled with the names of springs investigated in this study. The two western-most springs, Brelsford and Cook, are shown on USGS Geologic Maps in the Upper Member of the St. Louis Limestone (Brelsford, GQ412) and in the Ste. Genevieve Limestone and Upper Member of the St. Louis Limestone (Cook, GQ-710). These are primarily nomenclature changes relative to quadrangles east of this area and for the purposes of this report are considered to be equivalent to the lower portion of the Ste. Genevieve.

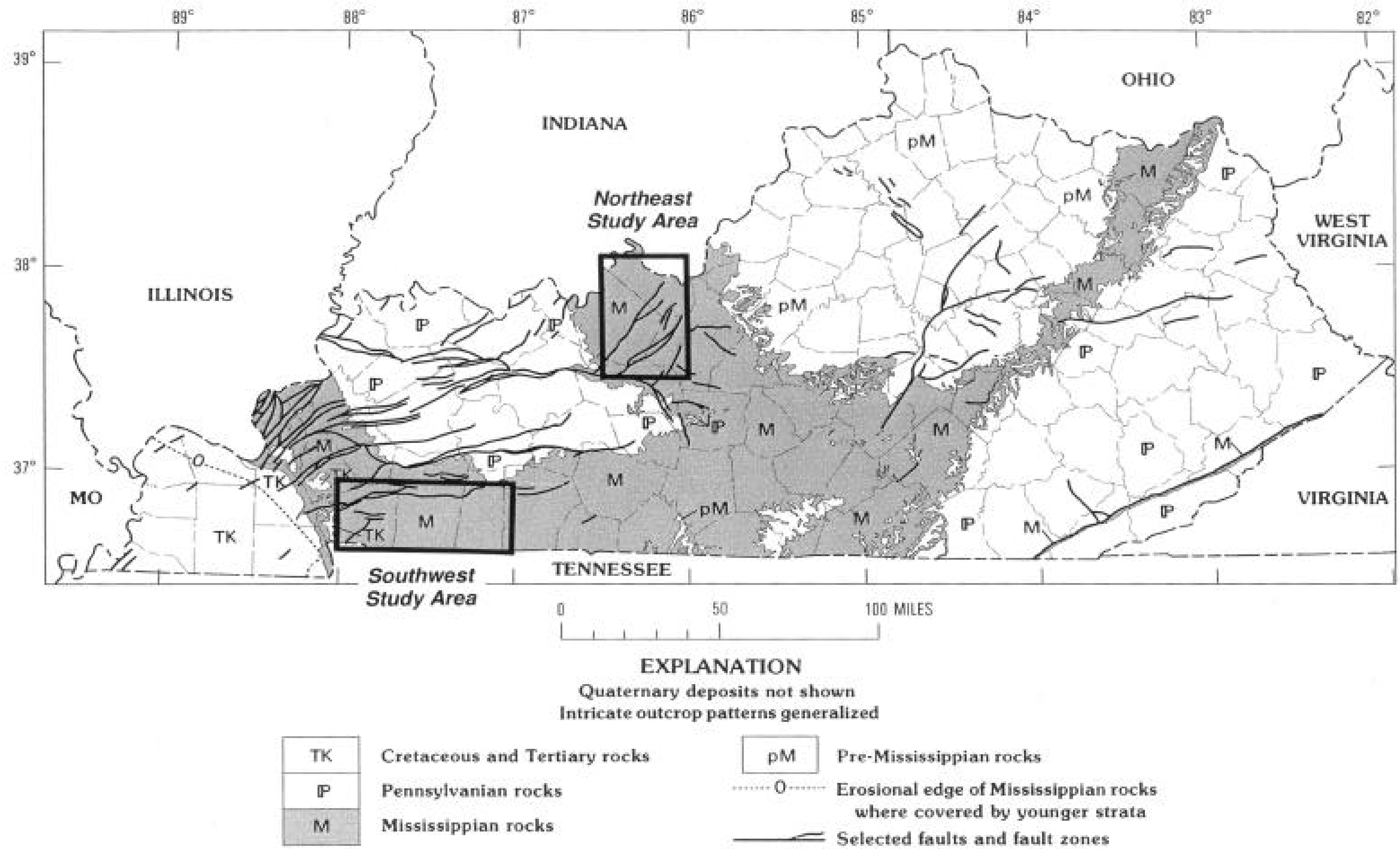

Figure 1: Index Map Showing the Location of two Study Areas within the Mississippian Plateau, Kentucky (Index base map adapted from Sable and Deaver, 1990).

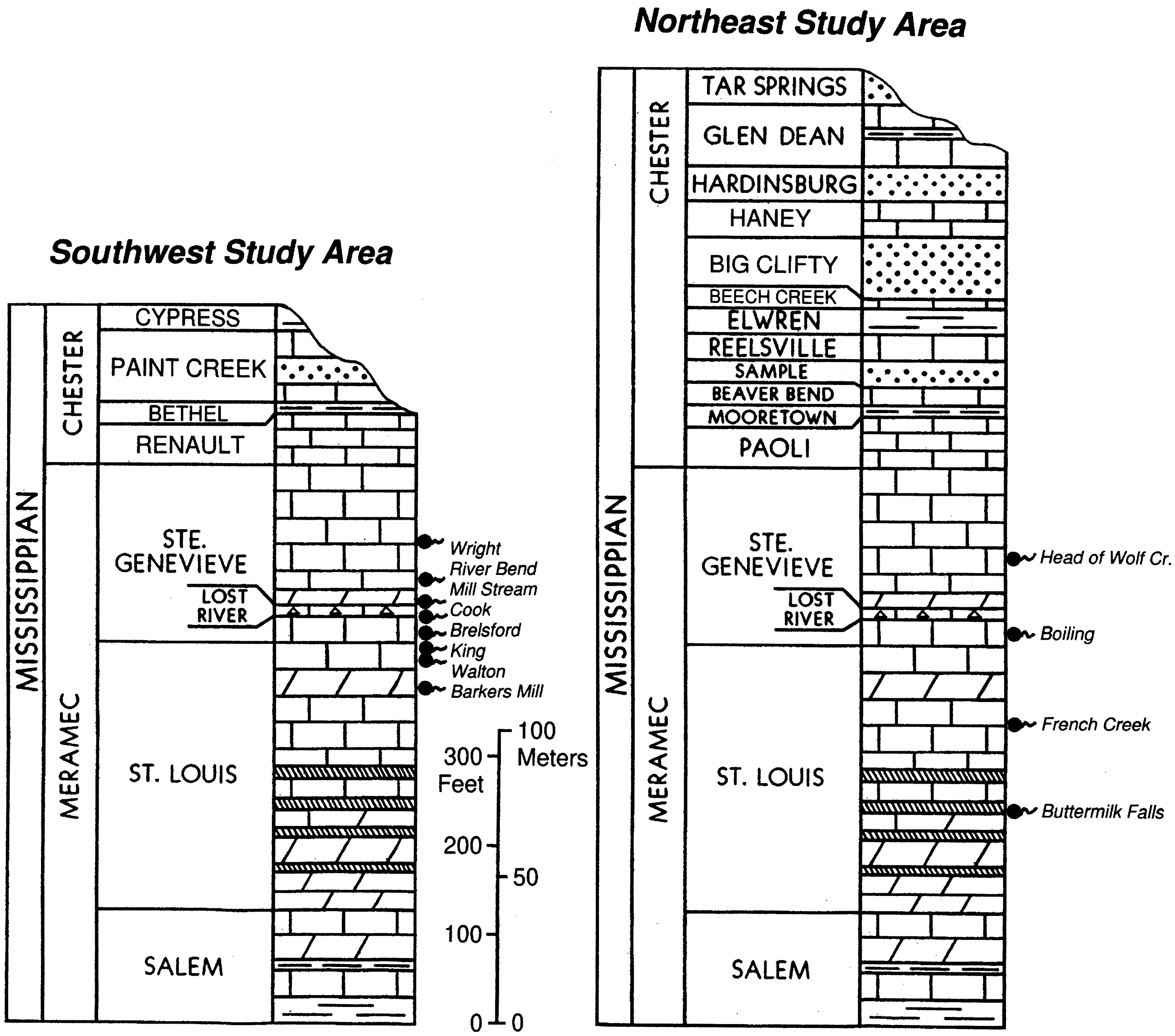

Figure 2: Generalized Stratigraphic Columns of the Southwest and Northeast Study Areas, Adapted from Ettensohn and Dever (1979)

The triangle-symbols labeled as Lost River near the base of the Ste. Genevieve Limestone, indicate a persistent chert horizon that tends to influence topography and groundwater flow. The diagonally hatchured zones in the lower section of the St. Louis Limestone identify gypsum and anhydrite beds. The lower portion of Chester-age rocks illustrate the similar lithology in both study areas but a regional variation in nomenclature. In the southwestern study area the units are named Renault, Bethel, Paint Creek and Cypress, whereas in the northeastern study area these units are named Paoli, Mooretown, Beaver Bend, Sample, Reelsville and Elwren. For the purposes of this report these rock units are considered to be equivalent.

Ste. Genevieve Limestone

Most of the karst drainage basins investigated in this study are developed within the Ste. Genevieve Limestone. The Ste. Genevieve is composed of thick-bedded, light-colored, medium- to coarse-grained, oolitic and bioclastic calcarenite; light-colored to gray, bioclastic calcirudite; gray calcilutite; and gray, very finely crystalline dolomite. Minor amounts of chert occur as nodules, thin beds and stringers, and siliceous replacements of fossiliferous beds. The Ste. Genevieve typically ranges in thickness from 55-73 m (180 to 240 ft) in the study area (Sable & Dever, 1990). The Lost River Chert is a distinctive 1-3 m thick zone of nearly continuous chert that occurs at, or near, the base of the Ste. Genevieve Limestone. This chert is highly fossiliferous with fenestrate bryozoans, brachiopods and gastropods. It is nearly indistinguishable from surrounding light gray limestone when freshly exposed, but when weathered reveals characteristic porous blocks of chalky white chert stained with red soil. Because of its resistance to corrosion, this chert bed is suspected to perch water bodies such as the Waterworks Spring basin, near Bowling Green, Kentucky (Moody and others, 2000), and to decrease sinkhole density where it underlies the surface, such as the Bristow Plain east of Bowling Green (Quinlan & Ewers, 1981).

St. Louis Limestone

A few of the karst drainage basins in this study discharge from the top and middle of the St. Louis Limestone, which underlies the Ste. Genevieve Limestone. The St. Louis consists of a very fine-grained, micritic, cherty, argillaceous and dolomitic limestone. It is characteristically gray to dark gray, fossiliferous and thick bedded to massive (Sable & Dever, 1990). The upper part of the St. Louis Limestone is highly cherty which helps to locally perch groundwater. Although this unit ranges from 90-145 m (300-475 ft) in thickness, most of the karst groundwater circulation relevant to this study occurs in the upper portion.

KARST HYDROLOGY

Because of the characteristics of karst terrane, rates of groundwater recharge, flow velocities and potential dispersion within the study areas can be extremely high. These groundwater systems can be rapidly recharged by widespread influx of precipitation and snow melt through soil macropores, runoff into sinkholes and concentrated flow from losing and sinking streams. Groundwater flow velocity through conduits often matches runoff in surface channels, which may travel several kilometers per day. Likewise, karst groundwater flow can be dispersive, potentially distributing pollutants over broad areas at a relatively long distance from the source. Three major hydrologic parameters of *recharge, flow and dispersion* were used to assess the groundwater sensitivity to pollution from surface activities in Kentucky (Ray, and others, 1994). Hydrogeological sensitivity was rated on a scale of 1 (low) to 5 (high), based on quantitative assessments of these three parameters. Documentation of conduit-flow velocities in karst aquifers by numerous tracer tests was especially useful for rating the important *flow* component in a particular hydrologic setting. In the karst terrane of the Mississippian Plateau, *recharge* porosity can range up to several meters, which is exemplified by stream insurgence into a cave or vertical shaft. *Flow* velocity within trunk conduits may range from 10 m/hr at low flow to 800 m/hr during flood conditions (Ray & O'dell, 1993). *Dispersion* of contaminants within this karst aquifer is usually linear or bi-directional, but widespread to radial flow patterns do occur. Because of these extreme ranges, the study areas are rated as “5,” which is the most sensitive hydrogeologic setting for potential pollution from surface activities and nonpoint sources.

The karst aquifers of Kentucky, formed in dense Paleozoic carbonates, typically contain low to moderate long-term storage of groundwater (White, 1988). Most seasonal groundwater storage is within the soil/regolith cover, the underlying weathered bedrock zone called the *epikarst*, and in bedrock fractures. Long-term storage within the epikarst, commonly in the form of a perched water zone, continually seeps and percolates down fractures and shafts and collects within the regional conduit drainage network. The karst flow system is typically an interconnected dendritic or branched horizontal network that discharges at large springs (Palmer, 1990). These convergent conduit networks tend to form distinct, contiguous groundwater drainage basins. Hydrologic interconnections between basins are typically localized along basin boundaries. However, inter-basin transfer from one trunk conduit to another may occur locally during overflow (high-water) conditions. Near the basin discharge zone, divergent distributaries are common and are usually overflow networks (Ray, 1997). Perennial-flow distributaries are less common.

Hydrogeology of the Northeastern Study Area

The principal aquifer in the NE study area is developed in up to 150 m (500 ft) thickness of the Ste. Genevieve and St. Louis limestones. These limestones generally dip west to northwest at about 4-7 m/km (20-40 ft/mi). Surface elevations range between 300 m (985 ft) MSL near Ekron to 117 m (383 ft) on the Ohio River pool. The general elevation of the sinkhole plain is 185-215 m (600-700 ft). A minor fault zone including Locust Hill Fault and Cave Spring Fault trends northeast from the Rough Creek Fault Zone into the study area (Amos, 1976). The location of Fiddle Spring and the Flat Rock distributary may be influenced by these faults and possibly associated lineaments. Average rainfall is about 115 cm/yr (45 in/yr).

Whereas most regional springs are located in the Ste. Genevieve, springs flowing directly into the Ohio River discharge from the underlying St. Louis limestones. The northeastern portion of this study area is predominantly a stream-less, low-relief karst plain, dominated by sinkholes or dolines. The dissected Dripping Springs Escarpment or Chester Cuesta, in the higher-relief western portion, contains up to 70 m (230 ft) of alternating carbonate and siliciclastic units of the Chester Series of the Mississippian System. These include the Glen Dean Limestone, Hardinsburg Sandstone, Haney Limestone, Big Clifty Sandstone, Beech Creek Limestone, Elwren Sandstone (sandstone and shale), Reelsville Limestone, Sample Sandstone, Beaver Bend Limestone, Mooretown Formation (shale, siltstone, and sandstone) and Paoli Limestone. The interstratal soluble beds often develop minor springs perched on underlying sandstones or shales. These springs typically sink at the contact with the next lower limestone. This alternating surface and subsurface flow is typical within the dissected plateau.

The main surface drainage in the high-relief area is Sinking Creek, one of the largest losing streams in Kentucky. This system heads at Blue Fork and Stoney Fork springs, in eastern Breckinridge County, and gains substantial flow from the Flat Rock Spring distributary and

Fiddle Spring just NW of Rosetta. The main losing reach of Sinking Creek is about 5 km (3 mi) south of Irvington. A meandering 19 km (12 mi)-long dry channel trends NW from the losing reach to Boiling Springs, where Sinking Creek resurges (George, 1976; Ray, 2001). Webster Cave is an overflow distributary of the Sinking Creek system discharging at Webster Overflow Springs. Trunk groundwater flow from Sinking Creek can be observed in a cave-stream segment at the southern reach of this extensive cave. The cave-stream level declines as much as 15 m (50 ft) during flow recession (Bell, 1976). Trunk flow can also be observed in Penitentiary Cave, about one km east of Boiling Springs (Angelo George, written communication, 2001). Additional springs in the area include Hardin Springs, which discharges from the south into Sinking Creek, about three km (1.9 mi) southwest of Boiling Springs. About 8 km (5 mi) WNW of Boiling Springs, Burtons Hole Spring and runoff from Sugar Tree Run and Dry Valley drains from the north. Sinking Creek ultimately flows into the Ohio River at Stephensport.

Hydrogeology of the Southwestern Study Area

The principal aquifer in the SW study area is developed primarily in up to 200 m (650 ft) thickness of the Ste. Genevieve and St. Louis limestones. Perennial master streams are fairly common within this low-relief karst plain although sinkholes, karst windows, and losing and sinking streams exist locally. Low-relief surface drainage networks tend to influence the overall karst landscape to a greater extent than classic sinkhole-plain topography as found in the NE study area or the Mammoth Cave region. The main streams of the area are Little River and West Fork, which are moderately incised to depths of about 40 m (130 ft). Major tributaries of Little River include Muddy Fork, Sinking Fork, Casey Creek and the North and South Forks of Little River. Major tributaries of West Fork include Little West Fork, Montgomery Creek and Spring Creek. Another stream, Elk Fork is a northern tributary of Red River. Average rainfall is about 127 cm/yr (50 in/yr).

Jillson (1927) discussed the stream-dissected, fluvial character of much of the landscape in the western Mississippian Plateau. He termed the plateau west of Bowling Green "Karst," and described it as widely pitted with sinkholes, but with only partial subterranean drainage. This western area was distinguished from the region northeast of Bowling Green, which was described as a "Sink Hole" region, where most of the drainage is subterranean. The fluvial character of the western region is probably related to reduced stream incision depths, the influence of bedded cherts (such as the Lost River Chert) within the limestones, and thicker regolith cover in the far southwestern portion of the region. Karst basins in the southwestern part of the Mississippian Plateau tend to be smaller than those to the east, where drainage is controlled by the more deeply incised Green, Barren, and Ohio rivers. Still, most drainage in the southwest is subterranean, even though surface drainage networks are more pronounced and perennial streams are more common than in the eastern portion.

One distinct difference between the eastern and western Mississippian Plateau is the more common occurrence of intermittent and seasonal lakes in the west. The relatively shallow depth to trunk conduits allows groundwater to rise to the surface during large floods and be stored in surface depressions, sometimes for months at a time (Crawford, 1981; Currens and Graham, 1993). This storage may be aggravated where the lateral transport capacity of shallow conduit networks is limited by constrictions or immature development (Aley and Thomson, 1981). Also, the more fluvial characteristic of this karst terrane also generates channelized (concentrated overland flow) storm-water runoff, which fills swamps, broad depressions, sinking stream basins, and locally disrupted valley segments. Because of this occasional phenomenon, flood-vulnerable development should not take place within closed topographic depressions (Ray, 2001).

METHODS OF INVESTIGATION

This investigation contains six basic components: Review of previous investigations and literature, hydrogeologic inventory, groundwater tracing, unit base-flow assessment, water chemistry sampling and land-use assessment. The Results of Groundwater Investigations section describes the springs and groundwater tracing data within basins, unit base flow assessment, and classification of karst basins. The Interpretation of Results section evaluates land cover and spring chemistry data and discusses the priority ranking of spring basins based on those data.

REVIEW OF PREVIOUS INVESTIGATIONS AND LITERATURE

Several previous investigations, concerning geology, hydrology and speleology have been conducted in or adjacent to the karst regions studied in this project. These investigations are summarized below and referenced under the appropriate **Spring** sub-heading in the **Results of Investigation** section.

Division of Water Investigations (Delineation of Spring and Wellhead Recharge Areas)

Northeast Study Area:

Ekron Public Water Supply Wells: In 1998, the Groundwater Branch conducted a groundwater tracer investigation of four public water supply wells at Ekron, in Meade County, Kentucky. The well at the Ekron Elementary School is 45 m (148 ft) deep, whereas the three wells supplying Ekron are of unknown depth. The site is a well-developed sinkhole-plain. This study was conducted by continually monitoring the wells with a pump-supplied garden hose tipped with a flow-through charcoal dye receptor. About 0.03 L/s (0.5 gallons per minute) of flow was continually passed through the charcoal during the study. While the wells were being monitored, fluorescent dyes were injected into sinkholes, sinking streams or Class V storm-water injection wells in the area. Although the wells were not known for turbid water, which often indicates a direct surface connection, all four wells received dyes injected into sinkholes within 300 m (1000 ft). Therefore these wells were shown to be under the influence of surface water. These tests also revealed that the flow systems were rather complex since some sinkhole dye injections were not detected, even though they were within 300 m of a well. All traced groundwater from the area around Ekron was eventually detected at Hamilton Hill Bluehole, 11 km (6.8 mi) north-northwest, which discharges to the Ohio River. These traces were the first to be recovered in Hamilton Hill Bluehole and helped to identify the southeast portion of this basin.

Battletown and Payneville Elementary School Wells: In 1998, the Groundwater Branch conducted groundwater tracer investigations of two water supply wells located at elementary schools in Battletown and Payneville. The sites are on top of ridges formed of alternating limestones and sandstones that are deeply dissected. Six traces were attempted near the 475 ft deep Battletown well, four of which were not recovered. This is probably due to summertime conditions and the small amounts of dyes used. The conclusion from this study was that the well may be effectively isolated from the active karst system by local hydrologic perching units with the ridge, the deep casing depth, and the limited pumping rate of 0.6 L/s (10 gpm). One dye trace was recovered in Oolite Spring discharging to the Ohio River east of the Battletown well.

During the Payneville Elementary well study, four dyes were injected in the area around the school. Three traces were recovered in Head of Wolf Creek Spring, 9-10 km (6-7 mi) to the northwest, but not in the 480 ft deep well. The conclusion was that, like Battletown, the Payneville well derives supply primarily from the fractured limestone aquifer that is not closely connected to the main karst drainage system. The three traces recovered in Head of Wolf Creek Spring, 9-10 km (6-7 mi) to the northwest, are the only traces to identify this basin. They show that this is a sizable basin and at an estimated low flow of 15 L/s (0.5 ft^3/s), not all of the potential base flow is observed at the known discharge point. Therefore, Head of Wolf Creek Spring is a seasonal overflow spring with perennial flow from a local sub-basin.

Southwest Study Area:

Merriwether Spring Groundwater basin: The recharge area of Merriwether Spring, Guthrie, Kentucky's, sole water-supply source at that time, was delineated with eight groundwater tracer tests conducted by Groundwater Branch personnel (Ray and Stapleton, 1996). The basin area is about 30 km^2 (11.5 mi^2) of primarily farmland. Merriwether Spring has a base flow discharge of 71 L/s (2.5 ft^3/s). The spring is a relatively constant-flow spring because most high-flow waters are discharged through a well-integrated subsurface overflow distributary from three springs at the southwest margin of the basin. Two of these springs are fed by conduits that pass beneath surface drainage to discharge on the far side of Spring Creek. Also, two surface overflow channels may be activated during high-flow conditions.

Trenton Water Well: The recharge area of a conduit-intersecting 27 m (90 ft)-deep water well, the water source for Trenton, was delineated by Groundwater Branch personnel during 1996-98. Eleven dye tests were conducted to identify a 17.6 km^2 (6.8 mi^2) sub-basin, centered on a sinking stream named Dry Branch, within the Hughs Bluehole karst drainage basin. In a normal year this sub-basin should yield a low-flow discharge of about 40 L/s (1.4 ft^3/s) whereas maximum pumping rate of the well is 19 L/s (300 gpm or 0.7 ft^3/s).

Pembroke Water Well: The recharge area of a conduit-connected 34 m (110 ft)-deep water well, the former water source for Pembroke, was delineated by Groundwater Branch personnel during 1997. Five dye tests were conducted which determined that the well was hydrologically connected to an unnamed losing stream with a watershed area of about 22 km^2 (8 mi^2), located northwest of Pembroke. The losing stream resurges at Hargrove Spring, 1.6 km (1 mi) to the south-southeast. Three other dye injections into local sinkholes indicated that the well's local recharge area extends outward as much as 120 m (395 ft) but less than 360 m or 470 m (1180 or

1540 ft). Therefore, a 305 m (1000 ft)-radius local recharge area was established around the well in addition to the losing stream watershed. In a normal year the losing stream sub-basin should yield a low-flow discharge of about 45 L/s (1.6 ft^3/s) whereas the maximum pumping rate of the well, per eight-hour shift, is 6.3 L/s (100 gpm or 0.22 ft^3/s). Because the well was reputedly non-turbid after heavy rains, whereas the losing stream was often turbid, some filtration mechanism must function in the recharge zone of this high-volume well.

Todd County Water Well: Division of Water Groundwater Branch personnel delineated the recharge area of a conduit-connected 37 m (120 ft)-deep water well, the water source for Todd County Water District, in 1997. Six dye tests were conducted which determined that the well was hydrologically connected to Elk Fork at some point or points about 305 m (1000 ft) northeast of the well. The Elk Fork watershed contributing to the well is 29.15 km^2 (11.25 mi^2) and the low flow of Elk Fork was estimated at about 15 L/s (0.5ft^3/s). Based on these values, the unit base flow of Elk Fork is calculated at only 0.04 $ft^3/s/mi^2$. The maximum pumping rate of the well, per eight-hour shift, is 6.3 L/s (100 gpm or 0.22 ft^3/s) or nearly half of the available low flow of Elk Fork. Therefore, drought could seriously impact the supply for this water well.

Additional Data from Literature

Fracture Control of Dolines, Caves and Surface Drainage, Kastning and Kastning (1980)

In the Sinking Fork/Caledonia area of the SW study area, fracture analysis from topographic maps, cave maps, aerial photographs and field inspections suggests that sinkhole (doline) alignments and straight-line stream reaches have been influenced by regional structures radiating or diverging from the west. Most caves of the area generally follow dominant fracture traces along major structural trends. Likewise, the orientation of much subsurface drainage suggests fracture control because of alignment of stream sinks, collapse areas, and springs.

Influence of Master Stream Incision on Cave Development, Trigg County, Moore and Mylroie (1979)

In Trigg and Christian counties, the incision of Sinking Fork into limestones has resulted in two basic patterns of cave formation: (a) meander cutoff caves formed by Sinking Fork drainage and (b) tributary caves transmitting drainage from the adjacent plateau to Sinking Fork. This study documented the aquifer diversion of Sinking Fork through Pipeline Cave and Boatwright Hole to Mill Stream Spring, 5.5 km (3.4 mi) to the east. This cutoff reduced the water flow path by 8 km (5 mi) resulting in a steepened gradient.

Meander Cutoff Caves and Self Piracy, Mylroie and Mylroie (1991)

This paper discusses the same topic as above and suggests that Cool Spring is recharged by piracy of Stillhouse Branch and that Steele Branch drains to Decibel Cave. Additionally, cutoffs on West Fork are described. Murphy Spring and Turners Bluehole are assumed to be cutoff springs. However, a replicated dye trace from the Watts Cave karst window to Turners Bluehole (01-22-JAR [Year-Dye trace number-Author's initials]) demonstrates that the spring, lying on the west side of West Fork, is the discharge point for a groundwater basin on the east side of West Fork. Conduit flow draining the basin is confined beneath West Fork. The basin of Murphy Spring is presently unknown but existing information supports the assumption that it is primarily fed by a cutoff from West Fork.

Groundwater Flow in the Vicinity of Gracy, Crawford, 1987; Crawford and Mylroie (unpublished)

A gasoline spill near Gracy, Kentucky, occurred with the rollover of a tanker truck along US 68-KY 80 on September 11, 1986. The spill site appeared to be in the headwaters of Steele Branch, which drains southwest to Sinking Fork. Crawford (1987) conducted a groundwater tracer study and mapped local water levels to determine the actual path that contaminants were likely to follow. An unpublished manuscript by Crawford and Mylroie describes the hydrogeology and emergency response to this gasoline spill. Groundwater flow from the site did not follow the surface watershed south to Sinking Fork as might be inferred from the topography. Instead, subsurface flow was to the northwest towards a graben structure and then parallel to the structure to the west, crossing the structure to discharge at Cook Spring, 13 km (8 mi) to the northwest. In this case, dye tracing and potentiometric-surface mapping was vital to determine the actual discharge point of groundwater potentially contaminated with spilled gasoline. This is one of only two tracer tests to be recovered in Cook Spring and identifies a chain of four large karst windows.

Trigg County Landfill, Ewers and Idstein (1991)

A dye-trace investigation was conducted to determine the destination of potential drainage from the Trigg County Landfill, north of Cadiz. Dye placed into the up-gradient monitoring well at the landfill site was traced primarily to Cadiz "Town" Spring, the water supply for Cadiz. A minor recovery of dye was also detected at 139 Bridge Spring to the north and at Logjam Spring, to the southeast. The dye was not detected in the down-gradient monitoring wells for the landfill, indicating that these wells are not reliable as monitoring points for the landfill. This trace was the first to be recovered in Cadiz Spring.

Cadiz Spring Groundwater Basin Delineation, Ewers and others (2001)

This Wellhead Protection study was conducted to determine the boundaries of the groundwater basin contributing to the Cadiz Spring, the town's water supply source. Four dye injections partially delineated the groundwater basin of Cadiz Spring. Green #6 Spring appears to be connected to the main flow route feeding Cadiz Spring. Traces were also recovered in Cook Spring and Fault Line Spring, draining to Muddy Fork, and in Sinking Fork upstream of Oliver Spring #2. Interstate 24 appears to be outside the Cadiz Spring basin.

Fort Campbell Military Reservation

Since 1985, basin delineation on and adjacent to the Fort Campbell Military Reservation in southern Christian County has been conducted by the USGS (Taylor, 1996; Hileman, 1997; Hileman and Ladd, 1998), Ewers Water Consultant, and students from Eastern Kentucky

University (Ewers and others, 1989; Carey, 1985). Karst basins partially mapped include Buchanan/Herndon Overflow and Quarles Spring. Also, tracer testing has been conducted for several Class V injection wells near Oak Grove and the I-24/US-41A interchange. Basins partially mapped include Hunter Spring and Barkers Mill Spring.

Characteristics of Large Springs in Kentucky, Van Couvering (1962)

One of the 12 sampled springs, Mill Stream Spring, was studied during the 1950s by Van Couvering of the USGS, in cooperation with the KGS. Most of the data presented in this report was collected by Brown, Kulp, Lambert, Mull and Whitesides.

Mill Stream Spring, in Trigg County, is described as issuing at the head of a narrow deep gorge from the St. Louis Limestone at 120 m (395 ft) elevation *(However, the site is mapped at the base of the Ste. Genevieve Limestone on GQ-604).* It formerly powered a large mill. Fourteen discharge measurements were made from 1955 through 1960, with three measurements aborted due to high water during 1956 and 1957. The discharges ranged from 42.5 L/s (1.5 ft^3/s) to 5041 L/s (178 ft^3/s), a 118-fold increase. Water temperatures ranged from 46-65 degrees F, compared to average groundwater temperatures of 54-59 degrees F, showing the influence of losing stream flow rapidly contributing to the spring. In parts per million (ppm), bicarbonate ranged from 90 to 260, sulfate from 6 to 14, and chloride from 2 to 7.

The Van Couvering report provides data on two additional springs which were studied in the dye-tracing portion of the project, Garnett Spring and Head of Doe Run Spring (Schenley Spring). ***Garnett Spring***, in Trigg County, discharges from the St. Louis Limestone at an elevation of 125 m (410 ft) and was gaged 17 times from 1955 through 1960. The discharges ranged from 45 L/s (1.6 ft^3/s) to 821 L/s (29 ft^3/s), an 18-fold increase. Water temperature ranged from 50 to 58 degrees F. In ppm, bicarbonate ranged from 190 to 325, sulfate from 2 to 13, and chloride from 1 to 7.

Head of Doe Run Spring (Schenley Spring) in Meade County, discharges from the St. Louis Limestone at an elevation of 175 m (575 ft) and was gaged 24 times from 1952 through 1960, with one measurement aborted due to high water in 1956. The discharges ranged from 120 to 990 L/s (4.2 to 35 ft^3/s), an 8-fold increase. Temperature ranged from 54 to 59 degrees F. In ppm, bicarbonate ranged from 195 to 230, sulfate from 25 to 230, and chloride from 1 to 19.

Hydrologic Investigations Atlas HA-33, Brown and Lambert (1963)

Although seven of the eleven springs investigated in the NE study area were not shown on HA-33, data were provided for four springs:

Head of Doe Run Spring (Schenley Spring), in Meade County, has been extensively studied by the USGS. HA-33 provides the lowest recorded USGS discharge value for that period of 114 L/s (4.04 ft^3/s). This compares with a DOW low-flow measurement of 150 L/s (5.3 ft^3/s) (9-11-94) and a drought measurement of 93 L/s (3.3 ft^3/s) on 12-1-99 (38% less than the normal summer low flow of 150 L/s). Based on 150 L/s, the Head of Doe Run Spring ranks as the 18th largest-volume spring in Kentucky (Ray, unpublished data).

Head of Wolf Creek Spring, in Meade County, was listed in the HA-33 report at 91.5 L/s (3.23 ft^3/s). Flow observations by DOW revealed that the spring diminished to an estimated 15 L/s (0.5 ft^3/s) during summer low flow. With a tracer-identified drainage basin of at least 42.5 km^2 (16.4 mi^2), this spring should yield nearly 3 times this amount. Consequently, this spring must be considered a seasonal overflow feature with minor base flow contributed by local drainage. The USGS discharge must not be a low flow measurement, but an unrepresentative reading at some point during intermittent or seasonal overflow conditions. (A seasonal overflow spring with zero base flow in Todd Co. (related to Meriwether Spring) was likewise over-represented at 189.5 L/s (6.7 ft^3/s) in HA-34)

Head of Spring Creek Spring, in Meade County, was listed in the HA-33 report at 143 L/s (5.05 ft^3/s). Similar to Head of Wolf Creek Spring, DOW has determined that Head of Spring Creek Spring must also be a seasonal overflow spring, and the USGS value is unrepresentative. The partially delineated basin of ~96 km^2 (37 mi^2), should yield three times more low-flow runoff than the gaged discharge of 27.2 L/s (0.96 ft^3/s) (9-17-98). Interestingly, this spring has produced a remarkable bluehole feature with a dimension of 40 x 24 m (130 x 80 ft), a maximum measured depth of 10.3 m (33.8 ft) and a large gravel/cobble natural levee. However, the large volume of water in the bluehole is not adequately circulated during low-flow conditions to flush the tanic discoloration of water, causing it to appear stagnant. Neither of the perennial underflow springs related to Wolf Creek or Head of Spring Creek have been located. This is due to the unpredictable back-ponding of the spring run downstream by the impounded Ohio River.

Boiling Springs, in Breckinridge County, is listed on HA-33 at an estimated discharge of 31.6 L/s (1.1 ft^3/s). This is a serious underestimation of the flow of the region's largest spring. At 277.5 L/s (9.8 ft^3/s) (average of four low-flow measurements) Boiling Springs is the tenth largest spring in Kentucky (Ray, unpublished data). The 1999 drought-discharge was down at least 36% to 178.4 L/s (6.3 ft^3/s).

Hydrologic Investigations Atlas HA-34, Lambert and Brown (1963)

Within the SW study area, HA-34 provides discharge data on three of the eight monitored springs:

Cook Spring, in Trigg County, is estimated at 190 L/s (6.7 ft^3/s). This estimate is nearly twice the low-flow discharge measurements made by DOW. The spring was gaged four times from 1994-1999, ranging from 88-133 L/s (3.1-4.7 ft^3/s). The average of the lower three measurements is 93 L/s (3.3 ft^3/s).

Mill Stream Spring, was named on HA-34 and listed with a minimum measured discharge of 42.5 L/s (1.5 ft^3/s). DOW gaged the spring in 1993 at 90.6 L/s (3.2 ft^3/s) and a 1999 drought measurement was 70.8 L/s (2.5 ft^3/s).

Wright Spring, in Todd County, is estimated on HA-34 at 45 L/s (1.6 ft^3/s). DOW gaged the spring three times during base flow from 1995 and 1999, ranging from 14-34 L/s (0.5-1.2 ft^3/s), for an average of 25 L/s (0.9 ft^3/s).

A fourth spring is shown about 1.2 km (0.75 mi) southwest of the actual location of Barkers Mill Spring. On HA-34 this unknown spring is estimated at 20 L/s (0.7 ft^3/s), which is nearly an order of magnitude lower than the gaged flow of Barkers Mill Spring. At a discharge of 170 L/s (6.0 ft^3/s), Barkers Mill Spring is the 16th largest Kentucky spring and the largest known spring west of Logan County. Nine of the additional eleven springs studied in this region were not shown on HA-34.

Sinking Creek Hydrosystem, Angelo George (1970-76)

***Boiling Springs*:** Previous tracer tests were conducted in the Boiling Springs basin by Angelo George (1970-72 unpublished data) and others (Bell Engineers, 1974). A main flow route within Boiling Springs basin, from Big Spring to the springs on Sinking Creek, was dye-traced during caving expeditions from 1970-72. Extensive cave surveys were made in Big Bat, Webster and Thornhill Caves. This work mapped a major flow route from the karst windows at Big Spring, through Gilpin Karst Window, Ross Karst Window, to the Flat Rock Spring distributary. Although a connection between the distributary and Fiddle Spring was determined by George, dye was not recovered in Fiddle Spring during tracing of the Flat Rock Spring distributary by DOW in low- to moderate-flow conditions. An overflow connection between the two otherwise separate systems may exist.

Wellner and Fister (1989) conducted a tracer test from a disposal sinkhole, used by the Irvington wastewater treatment plant, to Boiling Springs. James Greer conducted two tracer tests in the headwaters of Stoney Fork Spring (1993, unpublished data).

***Hardin Springs*:** Watt Hole Karst Window was connected to Hardin Springs by George (unpublished data, 1976).

Potentiometric surface - Mississippian Plateaus, Plebuch, Faust and Townsend (1985)

A regional study of the potentiometric surface and water quality in the principal aquifer of the Mississippian Plateaus Region, Kentucky, includes the two study areas of this report. The primary purpose of the study was to provide a potentiometric map of the principal aquifer for determining the general direction of groundwater movement, to aid in determining possible paths of pollutant movement and to help in selecting drilling sites. A secondary purpose of the report was to describe the general water quality in the principal aquifer.

The principal aquifer refers primarily to the St. Louis and Ste. Genevieve limestones but may also include units of the underlying Fort Payne Formation, Warsaw (Harrodsburg) Limestones and Salem Limestone. Within the overlying Chesterian Series, the Renault Limestone, the Beaver Bend and Paoli limestones (or the Girkin Limestone, depending on the location in the plain) may also be considered part of the principal aquifer.

The delineation of karst drainage basins by tracer mapping provides a test of the primary purpose of the 1985 study; i.e., to help determine the general direction of groundwater movement and to infer possible paths of pollutant movement. In order to fulfill the stated purpose, the core of major groundwater basins should be suggested by a concavity of the potentiometric contours, and major basin divides should be inferred by contour convexities or potentiometric highs. Because the contour interval is 50 ft (15 m), this objective can be met in only a very general way. As pointed out by Schindel and others (1994), potentiometric surface maps can only be used for *very general* predictions about karst groundwater movement. Data for the map were collected from 1975 to 1982 and also from earlier studies since regional groundwater levels have remained relatively stable for at least a quarter of a century (p. 2). Unfortunately, the density of water-level data points and the frequency of data rejection were not presented. These data would have helped to indicate the level of subjectivity employed in mapping water-level contours.

Comparison of Potentiometric Contours with Tracer-Mapped Karst Basins

In the NE study area, groundwater gradient and therefore flow direction is suggested by 400 to 650 ft (122 to 198 m) elevation potentiometric contours. The trunk path within the ***Boiling Springs*** basin is fairly well identified, but flow in the headwaters tends to parallel the contours or cross convexities. ***Head of Wolf Creek Spring*** drainage is shown crossing a 400 ft (122 m) contour convexity and is therefore not suggested by the map. ***French Creek Spring*** drainage is reasonably indicated with flow perpendicular to contours, as is ***Hamilton Hill Bluehole***. No tracer data were developed for ***Buttermilk Falls***, but the contours appear reasonable. Because the outcrop of the Ste. Genevieve-St. Louis limestones is highly generalized and partially covered by Chesterian series units in the western and southern portion of the NE study area, several lengthy groundwater flow paths were identified outside of the generalized outcrop area. The potentiometric surface contours were extended into these areas, however.

Other spring basins where tracer data were obtained include ***Head of Spring Creek Spring*** where the trunk is indicated but the headwaters tend to parallel the 450 ft (137 m) contour or follow a convexity. ***Head of Doe Run Spring*** is fairly well indicated but with some flow parallel to contours in the headwaters. Two springs are poorly indicated: ***Burtons Hole*** drainage follows a prominent potentiometric ridge shown by the 450 (137 m) and 500 ft (152 m) contours. ***Hardin Springs*** drainage is perpendicular to a trough and ridge formed by the 450 ft (137) contour. These last two spring basins, and the destination of groundwater contaminants, would not be located if a search for aquifer discharge points was based on the potentiometric surface map.

In the SW study area, flow direction is indicated by 400 to 600 ft (122 to 183 m) elevation contours. ***Cooks Spring*** drainage is fairly well indicated, but with flow parallel to the 500 ft (152 m) contour in the headwaters. ***Mill Stream Spring*** drainage is well indicated with a prominent trough shown just north of Sinking Fork. ***Brelsford Spring*** drainage crosses contours in a perpendicular direction but no trough is shown. ***Walton Spring*** and ***King Springs*** are poorly indicated with flow perpendicular to two convexities in the 500 ft (152 m) contour. ***Wright Spring*** is shown draining perpendicular to a broad convexity in the 550 ft (168 m) contour. The two largest karst basins in the SW study area, ***River Bend Spring*** and ***Barkers Mill Spring***, are not well indicated by the potentiometric surface because of flow crossing convex contours. These major aquifer discharge points are not well suggested by the regional map.

In summary, the success of the regional water-level map in indicating groundwater and pollutant movement is marginal, with some of the largest spring basins, and therefore main aquifer discharge points, not inferred by the 50 ft-interval (15 m) contours. As stated by Plebuch and others (1985):

"Potentiometric maps, constructed from water-level data, indicate the general direction of movement but details of the local movement generally require other methods of study. Dye tracing is one such method and work on local water movement is being done in the Mammoth Cave area (see Quinlan and Ray, 1981). Some work on local water movement is also being done at Bowling Green, Kentucky, but much remains to be done in this regard throughout the entire Mississippian Plateaus region." (p. 32)

The current study fulfils the need for additional tracer-mapping of the principal aquifer for identifying local groundwater movement. This work is widely recognized as essential for the adequate protection of the karst groundwater system.

McCraken Springs Recharge Area Delineation, Taylor & McCombs (1998)

During a hydrologic study of the drainage area of McCraken Springs on Otter Creek (Taylor and McCombs, 1998), one dye trace was connected to Big Spring in the headwaters of the Boiling Springs basin. A second connection from 6 km (3.75 mi) to the east-southeast was documented in a supplementary dye trace in 2001. This work extended the known width of the Boiling Springs basin to greater than 28 km (17.5 mi). The Head of Doe Run Spring, which bounds Boiling Springs to the northeast, was partially delineated by three dye traces in the eastern part of the basin. A fourth, supplementary, dye trace in 2001 extended the basin to the south for a total basin length of 16 km (10 mi).

HYDROGEOLOGIC INVENTORY

Even though some information was available in the literature concerning the locations of springs and swallets in the SW study area, major areas were not evaluated by published reports. For example, only five springs were shown on USGS topographic maps that include the Little River and its major tributary, Sinking Fork. Consequently, a 72 km (45 mi) spring survey was completed by canoe in November 1997, and 24 additional km (15 mi) were surveyed by walking. Over 30 additional springs were mapped, ranging from 3-160 L/s (0.1-5.6 ft^3/s) (summer base flow). The largest inventoried spring was not known in the literature previous to this study even though it is estimated to drain a 70 km^2 (27 mi^2) basin. Surveys for springs, during previous Spring Protection Area studies by the Groundwater Branch, had been conducted on West Fork, Spring Creek and Elk Fork.

The NE study area is bounded by the Ohio River to the north. One unnamed spring at the head of Wolf Creek appears on the topographic maps of the area. Five additional springs ranging from 14-96 L/s (0.5-3.4 ft^3/s) and a three-spring distributary at French Creek have been previously mapped during Wellhead Protection Area investigations by the Groundwater Branch. These include three large bluehole features ranging from 15-40 m (50 to 130 ft) in diameter, which are apparent seasonal overflow springs. The underflow springs related to Head of Wolf

Creek Spring and Head of Spring Creek Spring have not been located. A search for these additional discharge springs was conducted by boat on the Ohio River during the fall of 1998. No karst features were detected along the channelized Ohio River. An unusual feature at the Head of Spring Creek is a natural levee composed of cobbles deposited around part of the large bluehole. This coarse deposit indicates the turbulence of flood discharges from this overflow spring.

Data from the long-term caving and hydrologic work of Angelo George were vital in the NE study area. Over the last several years, he has provided information on the Boiling Springs hydrosystem, Hardin Springs and Hamilton Hill Bluehole. A perennial underflow spring at the western part of the study area was predicted after the inventory of a large intermittent overflow spring near the confluence of Dry Valley and Sugar Tree Run (Gary O'Dell, personal comm., 1999). A search was launched for the underflow spring, which was discovered at the location of a narrow topographic contour reentrant, one km southwest near the mouth of Sugar Tree Run. The owner named this spring Burtons Hole Spring. The discharge could not be accurately gaged because of fluctuations in the flow of Sinking Creek, which is back-ponded by the impounded Ohio River. Based on the apparent basin area, the discharge is calculated at about 54 L/s (1.9 ft^3/s).

Tracer-injection points were selected through an iterative, step-by-step process where major trunk-flow features or estimated basin boundaries were targeted for tracer testing. Losing and sinking streams, karst windows, sinking springs, sinkholes, and a drainage well were tested by dye injections.

GROUNDWATER TRACING

Qualitative groundwater tracer tests, described by Quinlan (1986) and Aley (1999), were conducted using six non-toxic fluorescent dyes:

Uranine Conc [Disodium Fluorescein] (Color Index (CI) Acid Yellow 73)
Keyacid Rhodamine WT Liquid (CI Acid Red 388)
Ricoamide Red XB [Sulforhodamine B (SRB)] (CI Acid Red 52)
Eosine (CI Acid Red 87)
Phorwite AR Solution [Optical Brightener] (CI Fluorescent Brightener 28)
Keyamine Flavine 7GFF 500% (CI Direct Yellow 96)

As described by Schindel and others (1994) and Field and others (1995), these dyes are optimal for use in groundwater-basin delineation because of non-toxicity, availability, analytical detectability, low cost and ease of use. The first four dyes are adsorbed onto activated granular carbon and analyzed for presence and relative intensity using a scanning spectrofluorophotometer. The last two dyes are adsorbed onto unbleached cotton and analyzed for presence and relative intensity under a long-wave ultraviolet lamp at the Division of Water's laboratory in Frankfort, Kentucky.

Samples of the activated carbon dye receptors are washed with tap water and processed in a solution of 50% 1-propanol, 30% de-ionized water and 20% ammonium hydroxide (Smart Solution). The eluted samples from this study were analyzed at the Department of Geology's hydrogeology laboratory at Eastern Kentucky University prior to December 1998 and afterwards at the Division of Water's laboratory.

Background dye receptors were deployed, exchanged and analyzed prior to dye injection in the study area. These background dye receptors served as controls for comparison with subsequently recovered receptors. Dye receptors were typically exchanged weekly. Positive dye recovery was identified when fluorescence intensity was at least four times greater than the background, although fluorescence of positives typically exceeded background by more than ten times. Dye-trace results were recorded on Division of Water Dye-Trace Record Forms. These documents included dye injection site information and a detailed record of each dye receptor recovered during the study (Appendix A).

Tracer Tests

During this project, 42 groundwater tracer tests were conducted for the purpose of basin delineation. The results of these investigations will be discussed individually for each basin and are listed under abbreviated dye-trace ID numbers such as 99-20 (year-sequence of dye injection; the senior author was the principal investigator for all 42 traces). Recovered dye-intensity level is ranked by qualitative plus symbols which equate to the general confidence level of a positive dye-trace connection:

(?) = Inconclusive
(+) = Positive
(++) = Very Positive
(+++) = Extremely Positive

Tracer data for the 12 sampled basins are presented below as well as information gathered for 11 neighboring basins (7 in NE; 4 in SW). Individual dye-trace data forms are included in Appendix C. A diagram of each of the 12 karst watersheds shows the final results of flow-path mapping and approximate basin boundary (groundwater flow routes are reported as minimum straight-line to curvilinear distances, which are less than actual conduit pathways). Each basin diagram includes a tabulation of discharge, basin area, unit base flow (UBF) and percent agricultural land use.

Eighteen reconnaissance tracer tests have been completed within nine groundwater basins in the SW study area. More than 81 km (50 mi) of newly interpreted flow routes have been mapped or previous traces replicated. Seven newly identified groundwater basins, yielding a total summer base flow of about 565 L/s (20 ft^3/s), drain an area of about 280 km^2 (108 mi^2) of mostly agricultural watersheds. Unusual spring types documented within these basins include constant flow springs, seasonal overflow springs, perennial distributaries and conduit underflow of the bedrock channel in Little River.

Twenty-four reconnaissance tracer tests have been completed within ten groundwater basins in the NE study area. More than 180 km (112 mi) of newly interpreted flow routes have been mapped or previous traces replicated. Seven newly identified groundwater basins, yielding a total summer base flow of about 283 L/s (10 ft^3/s), drain an area of about 390 km^2 (150 mi^2) of agricultural and forested watersheds. 57 L/s (2 ft^3/s) of estimated base flow from the Head of Spring Creek basin and 23 L/s (0.8 ft^3/s) of estimated base flow from Head of Wolf Creek basin are not included in the above total. The discharge points of these two basins have not been located due to back-ponding by the impounded Ohio River. Other hydrologic features documented within the NE study area include large intermittent to seasonal overflow springs, groundwater flow beneath major topographic divides, and depressed unit base-flow discharge apparently due to minimal base-flow runoff from sandstone caprock.

UNIT BASE FLOW ASSESSMENT

In addition to tracer testing, another method of assessment called ***unit base flow,*** or normalized base flow, was applied to the karst basins in both study areas. Unit base flow (base-flow discharge per unit area) is a useful easily calculated parameter that is characteristic of the base-flow groundwater hydrology of various terranes. As applied to karst terranes, this water-balance assessment can be used to estimate the recharge area of springs, characterize their basins and assess hydrogeologic relationships (Carey and others, 1994; Quinlan & Ray, 1995; Brahana, 1997, and Paylor and Currens, 2001). Unit-base-flow analysis is based on the assumption that equivalent units of watershed within similar hydrogeologic settings and climate will produce about the same volume of base-flow groundwater runoff. When applied to a regional population of springs, the method can be useful to predict the occurrence of springs and unobserved discharge below stream level, infer sources of spring pollution and target hydrogeologic and dye-trace investigations (Ray and Meiman, 1998).

Unit base flow (UBF) is calculated by dividing the summer base-flow discharge (BF) by the apparent basin area (A): BF/A = UBF, to produce a normalized flow per unit area. For example, a spring discharge of 10 L/s divided by a drainage area of 5 km^2 equals a unit base flow of 2 L/s/km^2. An unknown basin area can be estimated from a representative base-flow discharge value if the UBF of a typical reference basin, from a similar hydrogeologic setting, is known. The low-flow discharge of the spring draining an unknown basin is divided by the UBF of the reference basin to derive an estimated area of the unknown basin: BF/UBF = A. For example, a spring discharge of 10 L/s divided by a reference value of 2 L/s/km^2 equals a drainage area of 5 km^2. Considering the generalization of discharge and basin-area measurements, UBF calculations should be rounded off to the nearest hundredth.

Within the Mississippian Plateau, hydrogeologic settings composed of karst plain developed on Ste. Genevieve or St. Louis Limestones generally yield a UBF ranging from 1.6 to 2.3 L/s/km^2 (0.15 to 0.2 ft^3/s/mi^2). The base-flow groundwater runoff tends to be similar, whether it is sinkhole-plain type or flat-lying, fluvial-network type topography. Terrain formed on Chester Series limestones, such as Renault Limestone and alternating limestone and sandstone sequences, yield less UBF than the Meramec Series units. Although measurements have not been taken for the Chester Limestones, the headwaters of Mill Stream Spring and Little River yield significantly less groundwater runoff than the southwestern portion of the watersheds. Mill Stream Spring, with a basin of 168 km^2 (65 mi^2) generates a depressed UBF of only 0.44 $L/s/km^2$ (0.04 $ft^3/s/mi^2$), even though the southern half of the basin is developed in the Meramec Series limestones.

In the assessment of a regional group of springs, anomalies of unit base-flow, above or below the typical range, may suggest measurement errors or differing hydrogeologic conditions. Usual causes of anomalies include: inaccurate discharge measurements or basin area estimates; inadequate discharge measurements due to undiscovered springs: differences in hydrogeologic settings or climate; and industrial, agricultural or urban activities and conditions such as excessive groundwater withdrawal or recharge and increased surface runoff. Extensive field investigations may be required to determine which of these situations cause an apparent anomaly. Although a recharge area can be estimated by the UBF method, the actual basin location can only be inferred and must be confirmed by tracer studies. Ray (2002) illustrated an example of attributing an inferred basin area to the wrong location, during the initial investigation of a complex artesian flow system in Boyle County, Kentucky.

UBF analysis based on mean flows for a particular site differs significantly from calculations based on summer low flow. Since daily mean flow includes all discharge data recorded over a period of time, including high flows, it is an inflated value, relative to summer base flow. The latter value reflects the sustained base flow discharge of a groundwater basin and is directly related to the basin size. Likewise, summer base flow can be reliably observed in the field over several months, typically from August to November, whereas mean flow is calculated from records kept over a much longer period of time. Therefore, the condition of mean flow is not easily recognizable in the field during karst hydrogeologic investigations or for targeting discharge measurements.

UBF assessment based on mean flows may be desirable for specific applications. For sites with available stream flow data, mean flow periods may be derived for specific months by means of a radar plot where monthly means are compared to annual means. The annual mean is represented as a concentric circle on the radar plot, whereas monthly means delineate an oval. The oval is skewed higher than annual mean in winter and lower in summer. Therefore, certain "magic months" are located where the two plots intersect (Campbell and Singer, 2001). The use of this technique requires a significant discharge database and targeted gaging of stabilized base flow during the graphically pinpointed magic months. This level of background information is rarely available for most karst springs and is not required to calculate useful water balance data.

Karst Water Withdrawal for Agricultural and Turf-grass Irrigation

Agricultural and turf irrigation appear to be growing in popularity in Kentucky. Application of the unit base flow method provides data on quantities of available groundwater runoff per unit area. From these calculations, prudent limits can be established for irrigation from groundwater and streams in karst areas. For example, within most of the Mississippian Plateau, if about 2.2 L/s (90 gpm or 0.2 ft^3/s) of groundwater is withdrawn daily and lost through evapotranspiration, this operation could extract the base flow runoff from the equivalent of a square mile of karst terrane. During drought conditions, as measured in 1999 and previous droughts (Lambert, 1976), spring discharge may be reduced by one-third to one-half of the normal flow. Obviously, several high-volume irrigation projects could significantly impact water quantity and dependent aquatic communities in karst areas. This is especially true during drought when dwindling water supplies are under greatest demand. Because of potential stress on karst drainage during high-demand periods, only lake storage is recommended for non-essential water withdrawal during summer low-flow and drought periods. Essential water withdrawal refers to those water supplies required to maintain human and livestock populations.

WATER CHEMISTRY SAMPLING METHODS

Groundwater samples from 12 springs were collected quarterly over two years, from 1-19-99 though 5-16-01. Water temperature, pH and conductivity were measured in the field using Cole-Parmer digital direct-reading (or equivalent) portable temperature-compensating meters and recorded on field data sheets. Discharge was either gaged or estimated and flow conditions were noted. The instruments were calibrated according to the manufacturers' instructions using standardized buffer solutions. After field measurements, all probes were rinsed in deionized water and stored appropriately. pH electrodes were stored in a solution of 10% KCl.

Water samples were collected as near to the spring water source as possible. Samples not requiring field filtration were collected by submerging the water sample container directly into the stream run, with the container opening oriented upsteam. Samples requiring field filtration (orthophosphate, total dissolved phosphorus, and dissolved metals) were collected in a disposable cubitainer, returned to the vehicle and filtered through a portable vacuum filtration system using a 0.45-micron filter. New filters and silicon tubing were used at each sample location. All sample containers were new. Preservatives were immediately added when required.

Chain-of-custody forms were completed for each sample. They included sample collection date and time, signatures of sampling and sample handling personnel and a work order for the laboratory. Samples were stored in coolers packed with wet ice for transport to the appropriate analytical laboratory and delivered within 48 hours. Advance notice of sample collection and delivery was given to the Kentucky Geological Survey (KGS) laboratory so that critical sample holding times would not be exceeded. The laboratory was responsible for laboratory QA/QC, selection of appropriate approved analytical methods and for reporting analytical results. Periodically, sample duplicates and QA/QC blanks were submitted to the DES laboratory to verify analytical results and decontamination procedures.

Laboratory Analyses

Water analyses for the following parameters, shown in Table 1, were conducted by the KGS.

INORGANIC-NONMETAL	Atrazine	Boron
Alkalinity	Butylate	Cadmium
Chloride	Linuron	Calcium
Conductance	Metolachlor	Chromium
Fluoride	Metribuzin	Cobalt
pH	Pendimethalin	Copper
Sulfate	Simazine	Gold
	Trifluralin	Iron
		Lead
NUTRIENT		Lithium
Ammonia-Nitrogen	**Insecticide**	Magnesium
Kjeldahl-Nitrogen	Chlorpyrifos	Manganese
Nitrate-Nitrogen	Diazinon	Nickel
Nitrite-Nitrogen	Endosulfan	Phosphorous
Orthophosphate	Malathion	Potassium
	Permethrin	Selenium
		Silicon
RESIDUE		Silver
Total Suspended Solids	**Fungicide**	Sodium
Total Dissolved Solids	Chorothalonil	Strontium
Total Organic Carbon		Sulfur
Total Recoverable Phosphorus		Thallium
	INORGANIC METALS	Tin
	Aluminum	Vanadium
ORGANIC	Antimony	Zinc
Herbicide	Arsenic	
Acetochlor	Barium	
Alachlor	Beryllium	

Table 1: Analytical Parameters

LAND COVER ASSESSMENT

Digital land-use data for the study areas were obtained from the National Land Cover Data Set for the conterminous United States developed by the U.S. Geological Survey. They were first completed in 1992, and an accuracy rate of about 66% is expected. Within the 12 sampled basins, five primary types were identified which incorporated land-cover percentages of 3% or greater. The largest three categories included *Deciduous Forest* and two agriculture types, *Pasture and Hay* and *Row Crops*. Two additional minor categories included *Mixed Forest* and *Woody Wetlands*. These five types accounted for land cover totals within the spring basins ranging from 92%-98%. Additional secondary land-cover types, such as *Urban/Residential, Recreational Grasslands, Water, Limestone Quarry, Evergreen Forest, Emergent Herbaceous Wetlands and Transitional* are identified in the legend of individual basin maps when they are visually significant.

RESULTS OF GROUNDWATER INVESTIGATIONS

Four karst springs were selected for investigation in the NE study area, and eight springs were selected in the SW study area. Springs were chosen based on a lack of previous water-quality data, accessibility and a high percentage of karst terrane with agricultural land use. NE springs include Boiling, French Creek, Head of Wolf Creek and Buttermilk Falls. SW springs include Barkers Mill, River Bend, Cook, King, Brelsford, Mill Stream, Walton and Wright. A four-digit, unique Kentucky spring identification number is provided after the name of each spring. Brief descriptions of these 12 springs are given below with photographs, a basin map, basic measurements and dye-trace data. Figure 3 is a legend for the tracer data shown on these basin maps.

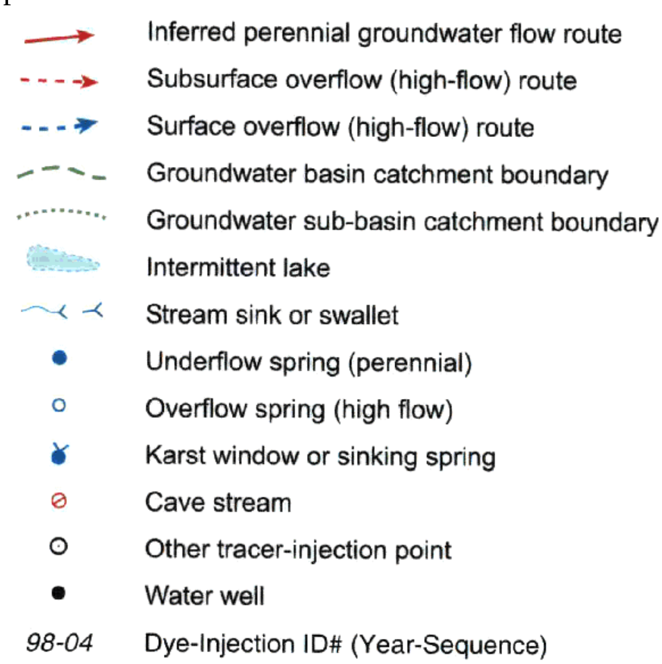

Figure 3: Legend for Tracer Data

DESCRIPTION OF SPRINGS AND BASINS, WITH SUMMARY OF TRACER TESTS

Northeast Study Area

Boiling (0855)

Boiling Springs (Figures 4a and 4b) is named at the northeastern corner of the Hardinsburg 7.5 minute Topographic Quadrangle, in north-central Breckinridge County [N37°-52′-9″; W86°-22′-41″]. Discharging from the Ste. Genevieve Limestone (Amos, 1975), Boiling Springs is a large 18 m-wide (60-70 ft) alluviated bluehole near the mouth of a local dry ravine at about 124 m (408 ft) elevation. The spring develops a 180 m-long (600 ft) spring run to Sinking Creek, where ruins of an old water mill exist. Above the confluence of Boiling Springs, Sinking Creek, which is primarily an overflow channel, discharges about 5.6 L/s (0.2 ft^3/s) of local flow during summer low flow conditions.

Over eight years, Boiling Springs has been gaged six times during low flow, ranging from a high of 365 L/s (12.9 ft^3/s) to a low of 178 L/s (6.3 ft^3/s) during the 1999 drought. The typical low-flow discharge averages 277 L/s (9.8 ft^3/s). Flood flow has been estimated at 56,000 L/s (2,000 ft^3/s) (George, 1976), 200 times greater than low flow. Numerous overflow features have developed around the bluehole's perimeter, which indicate a large fluctuation in discharge.

Figure 4a: Boiling Springs

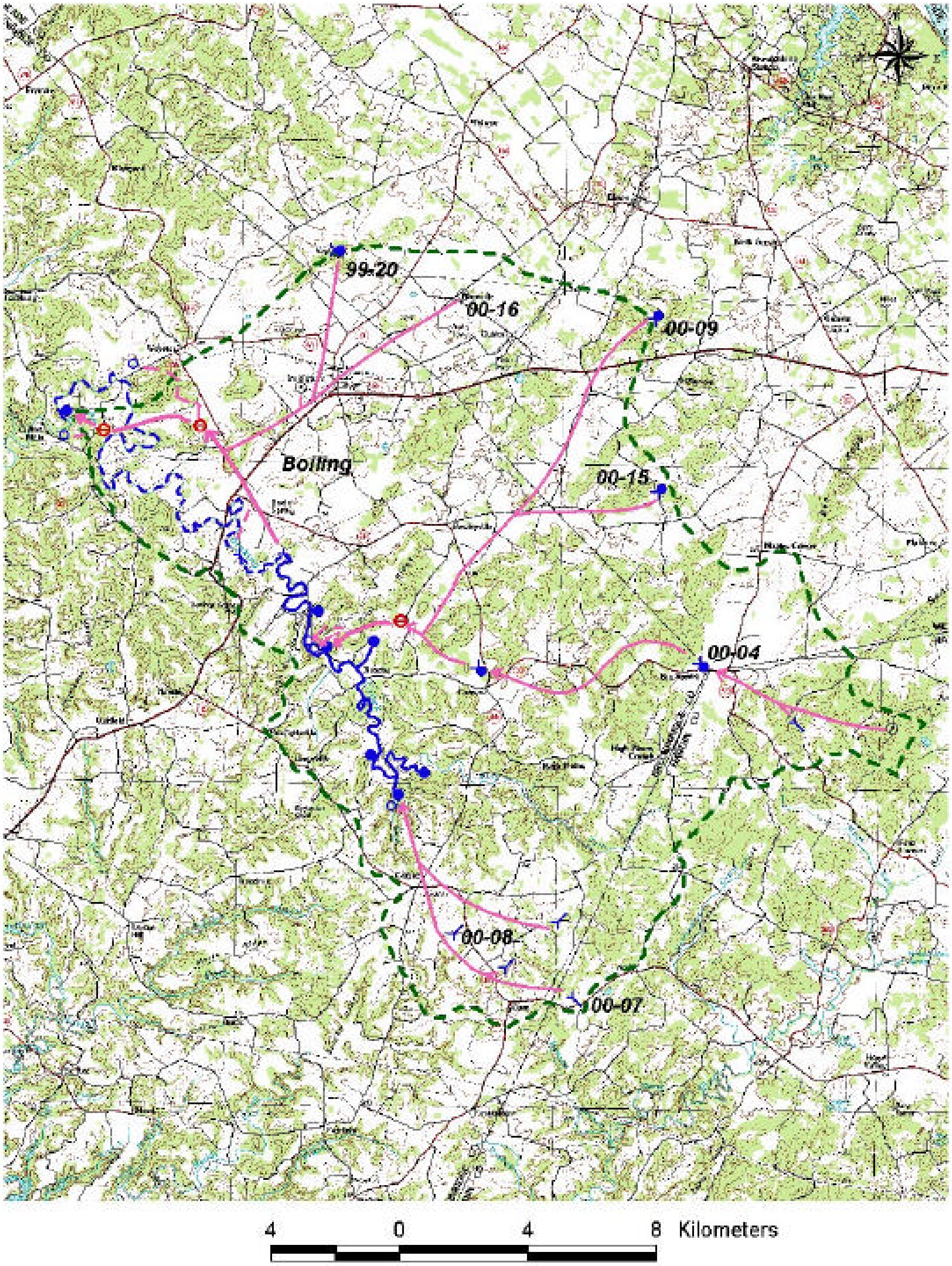

Figure 4b: Boiling Springs Basin:
Low-Flow Discharge 277.5 L/s (9.8 ft^3/s); Basin Area 327.6 km^2 (126.5 mi^2); UBF 0.87 $L/s/km^2$ (0.08 $ft^3/s/mi^2$); Land-use 52.7% Agricultural, 45.6% Forest

Large overflow springs exist about 2.5 km (1.5 mi) to the northeast near Webster. These are known to be related to Boiling Springs by cave mapping but they were not active during recent tracer studies. Additional overflow springs, which have developed a large pocket valley to the southwest near Clifton Church, are suspected to be related to trunk groundwater flow from the basin as well as floodwaters from Sinking Creek overflow channel to the east (George, 1978).

Although Boiling Springs is the eleventh largest volume spring in Kentucky based on low flow, it drains a basin of 327.6 km^2 (126.5 mi^2). This ranks as Kentucky's second largest known karst basin. Because of large flow capacity, all winter base flow discharges through the main spring, and consequently Boiling Springs yields the largest sustained winter base flow in Kentucky (estimated at about 1400-1700 L/s (50-60 ft^3/s).

Dye tests of Boiling Springs:

99-20

May 25, 1999: 765 g (27 oz) of fluorescein was injected at the swallet of a small sinking spring (**Millay Spring**) on Hogback Hill during moderate flow conditions. Within five days, an extremely positive dye recovery was made 7 km (4.4 mi) to the southwest at the spring run of Parks Spring (+++), while Boiling Springs and six other sites were negative. On April 15, a second dye receptor exchange indicated that Burtons Hole (+++), 15.5 km to the west-southwest, as well as Boiling Springs (+), 9.5 km to the southwest, were also positive. A third exchange on April 22 showed dye recovery in Burtons Hole (+) and Parks Spring (+) had diminished, while Boiling Springs (-) was negative.

Interpretation:

Parks Spring has an estimated low flow of 8.5 L/s (0.3 ft^3/s) (10-1-93), and contains nearby overflow features. With a calculated area of approximately 5 km^2 (2.0 mi^2), a direct connection between Millay Spring and Parks Spring, which are 6.5 km (4 mi) apart, is unlikely. Therefore, the dye recovery in Parks Spring is interpreted to have arrived from the Burton Hole basin via an overflow route. The arrival of dye in Boiling Springs, at a later date than Parks Spring run, appears to indicate that dye initially split along the groundwater basin boundary between Burton Hole and Boiling Spring.

Map data from A. George (written comm., November 2000) show a stream swallet about 2 km downstream from Parks Spring (Webster Bluehole). If this spring-run diversion, which most likely drains to Boiling Springs, was functioning during the dye trace, Boiling Springs should have been positive on the first exchange. This timing of dye recovery tentatively supports a separate, more lengthy, flow route though the Irvington area, within the Boiling Springs basin.

00-4

March 23, 2000: 400 g (14 oz) of eosine was injected into the swallet of **West Big Spring karst window**. This test was a replication of unpublished work within the Boiling Springs basin by George and others (1970). Within six days Gilpin Karst Window (++), Ross Karst Window

(++), Flat Rock Spring (++), 11.5 km (7 mi) to the west, were very positive, as well as two overflow springs just downstream. Board and Fiddle springs were not positive during these flow conditions, although higher-level overflow connections, as reported by George (1978), are possible.

00-7 Stoney Fork Spring sub-basin

April 18, 2000: 115 g (4 oz) of fluorescein was injected into a small stream **swallet** between **Dyer** and **Arch**, Kentucky. This trace was designed to test the southern boundary of the Boiling Springs basin. Eight days later, Stoney Fork Spring (++), 8 km (5 mi) to the northwest was very positive while six other sites were negative. This spring, a major headwater of Sinking Creek, was also positive 16 days after injection.

00-8

April 18, 2000: 115 g (4 oz) of SRB was injected at the **swallet** of a small sinking stream on the **Alexander** property. Eight days later, Stoney Fork Spring (++), 4.5 km (2.75 mi) to the north-northwest, was very positive while six other sites were negative. Traces # 7 and 8 confirm unpublished data by Greer (1993) that the headwaters of Muddy Prong have been pirated by the Sinking Creek/Boiling Springs system.

00-9

May 2, 2000: 225 g (8 oz) of fluorescein was injected at **Polly Brown Spring**, a minor sinking spring draining from an upland 4.25 km (2.5 mi) east of Guston. Seven days later, Head of Doe Run (+++), 6.5 km (4 mi) to the northeast, was extremely positive while springs in Boiling Springs' Sinking Creek system, 14 km (9 mi) to the southwest recorded the leading edge of the dye slug. Flat Rock Spring (++) showed peak dye recovery within 14 days. The results documented a groundwater bifurcation along a basin boundary and indicated a conduit-flow velocity of 2 km/day during moderate conditions. The southwest tributary dye vector also joined the main Big Spring trunk between Ross (+) and Gilpin (-) karst windows. Dye persisted in both basins for about three weeks.

00-15

May 16, 2000: 115 g (4 oz) of eosine was injected at **Hicks Sinking Spring**, which was designed to help define the boundary between Boiling Springs and Head of Doe Run basins. Sixteen days later, dye was detected at Flat Rock Spring (+), 11.5 km (7 mi) to the west-southwest, and Boiling Springs (+). Ross Karst Window was inconclusive (?) on June 7 and positive on the 13th (+). Dye detections were of low intensity during this trace, indicating that a larger quantity of dye should have been used.

00-16

June 1, 2000: In order to help define the northern boundary of Boiling Springs basin, 425 g (15 oz) of SRB was injected with 600 gallons of flush water into **Haysville Sinkhole**. Twenty and 35 days later Boiling Springs (+), 13 km (8 mi) to the west-southwest was positive while nine other sites were negative.

French Creek (1838)

French Creek Springs (Figure 5a) is a 305 m (1000 ft)-wide distributary of two perennial springs, which provide the base flow of French Creek in north-central Meade County [main spring to east: N38°-01′-44″; W86°-14′-28″/ western spring: N38°-01′-44.5″; W86°-14′-39″].

Figure 5a: French Creek Spring (Major Perennial)

An additional large overflow spring [N38°-01′-44.5″; W86°-14′-55″] as well as two ravines contributes high-flow discharge to the creek that ultimately drains to the Ohio River. A large cobble bar formed by the overflow spring indicates highly turbulent discharge (Figure 5b). None of these springs are shown on the Mauckport 7.5 minute Topographic Quadrangle nor are they reported in the literature. Discharging from the St. Louis Limestone (Amos, 1972) at about 121 m (396 ft) elevation, the two perennial springs appear as free-draining gravity springs and develop short, rapid spring runs to the main French Creek channel. The overflow spring, located about 1525 m (5,000 ft) up-channel at 128 m (420 ft) elevation, is a bluehole spring of unknown depth. The most likely conduit-plumbing explanation is that the two related gravity springs drain through constricted distributaries dispersing from the trunk conduit that feeds the overflow rise pit. The capacity of the perennial spring distributary may approximate the base-flow volume, which is easily exceeded during high flow, thereby forcing overflow water from the more elevated bluehole spring. Consequently, the perennial distributary may be classified as a free-draining gravity system, but with an artesian overflow spring up-channel of the perennial springs. The system discharged 45 L/s (1.6 ft^3/s) on 10-21-98 and 40 L/s (1.4 ft^3/s) during drought (9-7-99).

Figure 5b: French Creek Overflow Spring

Figure 5c: French Creek Springs Basin:
Low-Flow Discharge 45.3 L/s (1.6 ft^3/s); Basin Area 54.4 km^2 (21.0 mi^2)
UBF 0.87 L/s/km^2 (0.08 ft^3/s/mi^2); Land-use 67.9% Agricultural, 27.2% Forest

Dye tests of French Creek:

99-21

March 25, 1999: 600 g (21 oz) of SRB was injected into a small sinking spring named **Lawson Spring**, during moderate flow conditions. Five days later, the dye was recovered 9.5 km (6 mi) to the north-northeast in the French Creek distributary (++) but not in six other sites. The dye was also present at French Creek (+) on April 15 but negative thereafter.

99-28

April 30, 1999: 140 g (5 oz) of SRB was injected with 200 gallons of flush water into **Clark Sinkhole**. Six days later, the French Creek system was tentatively positive with only two grains of charcoal salvaged from a damaged dye receptor. The 11-day dye receptor was negative. M*ay 20, 1999:* The above inconclusive result prompted a replication with 450 g (16 oz) of fluorescein. Twenty-six days later, French Creek (++), 10 km (6 mi) to the north, was very positive and after 35 days, Hamilton Hill Bluehole (++), 9 km (5.5 mi) to the north, was also very positive. This trace indicated that Clark Sinkhole is near the boundary between the basins of French Creek Springs and Hamilton Hill Bluehole.

00-17

June 21, 2000: 400 g (14 oz) of fluorescein was injected with 400 gallons of flush water into **Dooley Sinkhole**. Forty-one days later, dye began to emerge from Hamilton Hill Bluehole (+), 11.5 km (7 mi) to the north, and grew stronger over the next few weeks. Nine weeks after injection, dye also began to emerge from French Creek springs (+), 12 km (7.5 mi) to the north. Dye recovery was delayed and prolonged because of low-flow conditions.

Buttermilk Falls (1824)

Buttermilk Falls Spring (Figures 6a and 6b) in north-central Meade County [N38°-00′-8″; W86°-09′-29″] is composed of two larger and four smaller perched springs discharging through a lateral spring horizon over a ~30 m (100 ft) outcrop of the St. Louis Limestone (Amos, 1972) at about 134 m (440 ft) elevation.

An additional minor spring is located next to an abandoned pump station about 60 m (200 ft) to the west. The main springs flow immediately through culverts beneath a limited-access gravel road paralleling the steep slope. Tufa deposits are located in the steep channels below the road. The springs are perched about 14 m (45 ft) above Flipping Creek, which borders the Ohio River bottoms. They discharge a combined 21 L/s (0.75 ft^3/s) during low flow (9-17-98).

During 1982, more than one hundred Meade County residents contracted hepatitis-A from drinking contaminated water from this spring. One fatality resulted from this outbreak (Environmental Quality Commission, Kentucky, 1992). An anecdotal dye trace by Meade County Health Center inferred the subsurface connection between a private septic system in Brandenburg and Buttermilk Falls Spring (Mull and others, 1989; P. Schultz, oral communication, 2002).

Figure 6a: Buttermilk Falls Spring

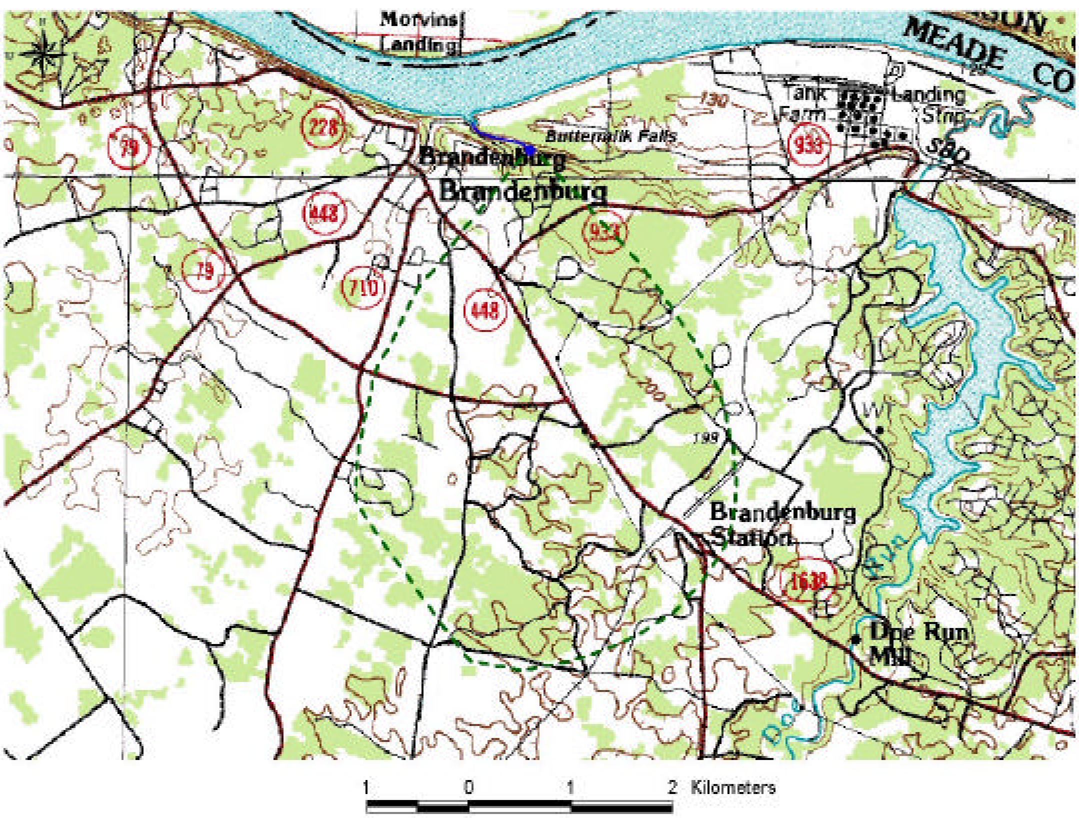

Figure 6b: Buttermilk Falls Spring Basin:

Low-Flow Discharge 22.7 L/s (0.8 ft^3/s); *Estimated* Basin Area 12.7 km^2 (4.9 mi^2);
UBF 1.7 $L/s/km^2$ (0.16 $ft^3/s/mi^2$); Land-use 26.8% Agricultural, 65.1% Forest